

COMPARING SHOCKS IN PLANETARY NEBULAE WITH THE SOLAR WIND TERMINATION SHOCK

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ABSTRACT

We show that suprathermal particles, termed pick-up ions (PUIs), might reduce the postshock temperature of the fast wind and jets in some planetary nebulae (PNs) and in symbiotic systems. The goal is to explain the finding that the temperature of the “hot bubble” formed by the post-shock gas in some PNs and symbiotic nebulae is lower, sometimes by more than an order of magnitude, than the value expected from simple hydrodynamical calculations. Although various explanations have been proposed, there is as yet no preferred solution for this “low temperature problem.” PUIs have been invoked to explain the low temperature behind the termination shock of the solar wind. While in the case of the solar wind the neutral atoms that turn into PUIs penetrate the pre-shock solar wind region from the interstellar medium (ISM), in PNs the PUI source is more likely slowly moving clumps embedded in the fast wind or jets. These clumps are formed by instabilities or from backflowing cold gas. Our estimates indicate that in young PNs these PUIs will thermalize before leaving the system. Only in older PNs whose sizes exceed ~ 5000 AU and for which the fast-wind mass loss rate is $\dot{M}_w \lesssim 10^{-7} M_\odot \text{ yr}^{-1}$ do we expect the PUIs to be an efficient carrier of energy out of the postshock region (the hot bubble).

1. INTRODUCTION

Central stars of young planetary nebulae (PNs) blow a fast wind that collides with the dense PN shell and becomes a thermal X-ray source (Volk & Kwok 1985). The postshock region of the fast wind is termed the hot bubble. About a third of PNs targeted by contemporary X-ray satellite observatories (either *Chandra* or *XMM*) have been shown to have extended X-ray emission (Kastner 2007). The other PNs either possess a hot bubble but their

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emission is below detection threshold, or the gas in the hot bubble escapes through a hole in the dense shell that was punctured by a jet (or jets). This last process deserves further study.

The simplest and most straightforward estimate of the expected hot bubble temperature is given by the Rankine-Hugoniot jump condition for the fast wind shock

$$T_{\text{fw}} = \frac{3}{16} \frac{\mu m_H v_f^2}{k} = 1.4 \times 10^7 \left(\frac{v_f}{1000 \text{ km s}^{-1}} \right)^2 \text{ K}, \quad (1)$$

where v_f is the fast wind velocity, and the other symbols have their usual meaning. This expression is widely employed in describing astrophysical shocks in general and PN wind shocks in particular (e.g., Zhekov & Perinotto 1996; Soker & Kastner 2003, and references therein). However, the observed temperatures, T_{H} , of the extended X-ray emission sources in nearly all PNs (Kastner et al. 2000, 2001, 2003, 2008; Chu et al. 2001; Guerrero et al. 2002, 2005; Sahai et al. 2003; Montez et al. 2005; Gruendl et al. 2006) are lower than the simple estimates obtained from Eq. 1, with $T_{\text{H}} \sim 1 - 3 \times 10^6 \text{ K}$ (Kastner 2007; Kastner et al. 2008). The ratio of the temperature given by equation (1) to the observed temperature ($T_{\text{H}} \sim 1 - 3 \times 10^6 \text{ K}$) ranges from $T_{\text{fw}}/T_{\text{H}} \sim 1.5$ (for one object, NGC 2392, adopting $v_f \simeq 400 \text{ km s}^{-1}$ [Tinkler & Lamers 2002] and a revised estimate of $T_{\text{H}} = 1.5 \times 10^6 \text{ K}$; Montez 2010, PhD thesis, RIT, in prep) to ~ 200 (NGC 7026, with $v_f \simeq 3500 \text{ km s}^{-1}$ and $T_{\text{H}} = 1.1 \times 10^6 \text{ K}$), with typical values of $T_{\text{fw}}/T_{\text{H}} \sim 10$. For the one case in which the values of T_{fw} and T_{H} might be consistent, NGC 2392, Tinkler & Lamers (2002) and Guerrero et al. (2010) report an anomalously slow wind speed of only $v_f \simeq 400 \text{ km s}^{-1}$. They further comment that the central star (CSPN) of NGC 2392 is unusual among CSPN blowing winds.

We term the evidence that the X-ray emitting gas in PNs possesses a temperature lower than that given by equation (1), $T_{\text{H}} \lesssim 0.1 T_{\text{fw}}$ the *low temperature problem*. Three different processes — possibly acting in combination — were proposed to account for this low temperature problem in the past:

1. *Heat conduction.* The hot ($T > 10^7 \text{ K}$) post-shock gas is cooled via heat conduction to the cooler nebular gas (Soker 1994; Zhekov & Perinotto 1996; Steffen et al. 2008), or via mixing with the cooler gas (Chu et al. 1997) enhanced by instabilities (Stute & Sahai 2006). However, Yu et al. (2009) have shown that the composition of the X-ray-emitting plasma in the hot bubble of BD +303639 is indistinguishable from that of the CSPN fast wind. There also exist preliminary indications that there is a sharp temperature jump between the hot bubble and the cooler nebular gas (Nordon et al. 2009). Hence it appears magnetic fields might inhibit heat conduction (Stute & Sahai 2006).

2. *Intermediate fast wind.* In this solution to the low temperature problem the X-ray emitting gas comes mainly from a slower moderate-velocity wind of $v_f \sim 500 \text{ km s}^{-1}$ blown by the central star during the post-AGB phase (Soker & Kastner 2003; Akashi et al. 2006, 2007).
3. *Hot lobes formed by jets.* The X-ray emitting gas comes mainly from two opposite jets or collimated fast winds (CFW; Soker & Kastner 2003; Akashi et al. 2008), expanding with velocities of $\sim 300 - 700 \text{ km s}^{-1}$. The jets are blown by a companion accreting mass from the AGB or post-AGB star. In this scenario, which is most obviously applicable to objects such as NGC 7027 — in which the X-ray morphology closely resembles that of high-velocity, collimated flows imaged in the infrared (Cox et al. 2002)— the X-ray properties are tightly connected to the shaping mechanism of the nebula.

As noted, some of these processes can coexist. For example, both the double opposite jets that have shaped the PN and the post-AGB (intermediate) central star fast wind might occur one after the other in a PN. Heat conduction and mixing between hot lobes and the nebular gas might then occur, further lowering the X-ray temperature below that expected given the present CSPN wind speed.

The low temperature problem is also evident in the case of some symbiotic nebulae (some formed by symbiotic novae) that possess jets. In the recurrent nova RS Ophiuchi the inferred jet velocity is $\sim 6,000 \text{ km s}^{-1}$, for which equation (1) gives a temperature of $\sim 5 \times 10^8 \text{ K}$, while the inferred jet X-ray temperature is only $\sim 10^7 \text{ K}$ (Luna et al. 2009). The low temperature problem also might exist in the case of the symbiotic nova R Aquarii, where the X-ray temperature of $1.7 \times 10^6 \text{ K}$ (Kellogg et al. 2007) is much below the expected temperature of $8 \times 10^6 \text{ K}$. If the underlying low temperature problem in these systems is the same as in PNs, then the explanation cannot be an intermediate fast wind, and we would need to appeal to one or both of the other processes described above.

As there is no consensus yet on the mechanism that explains the low temperature problem, in this paper we explore whether *pick-up ions* (PUIs) can solve the low temperature problem in PNs. In this process, initially slowly moving ions embedded (but not moving with) the fast wind are rapidly picked up by the fast wind and gain super-thermal energy relative to the wind; hence the term PUIs. In the shock wave the PUIs gain much more energy than the thermal particles and, hence, collectively act as a heat sink within the post-shock gas. If the number of PUIs is high enough, they can contain most of the post-shock energy and, in so doing, substantially lower the post-shock temperature of the thermal gas.

Measurements by the Voyager 2 spacecraft show unexpected plasma properties. For

example, these measurements indicate that the flow is still supersonic with respect to the thermal ions downstream of the termination shock of the solar wind (Richardson et al. 2008; Decker et al. 2008). Richardson et al. (2008) and Decker et al. (2008) conclude that most of the solar wind energy is transferred to PUIs or other energetic particles both upstream of and at the termination shock. It is these unique, *in situ* measurements of a wind shock that serve as the primary motivation for the work presented here. However, we note that PUIs also may represent a significant cooling mechanism in supernova remnants (SNR; e.g., Ohira & Takahara 2010 for a recent paper and more references). In SNRs the PUIs play a role mainly in the forward shock that runs ahead of the interaction region (Ferrand et al. 2010), while for the solar wind — and, as we demonstrate below, in PNs — the PUIs play a role in the reverse shock that runs into the stellar wind. In these latter systems the forward shock is a weak shock (i.e., has a low Mach number). While the physics of the shocks in SNRs and in PNs is the same, we argue below that the way the PUIs enter the pre-shock wind region is different.

Our study of the formation and behavior of possible PUIs in PNs is organized as follows. In section 2 we summarize the main relevant results of the PUIs in the solar wind. In section 3 we compare the properties of the solar termination shock to those of the fast wind in PNs, and in section 4 we study the constraints on the flow properties for PUIs to play a role in PNs. In section 5 we summarize our main results.

2. THE ROLE OF PICKUP IONS IN THE SOLAR WIND TERMINATION SHOCK

Many different ingredients and processes that occur in the solar wind and its termination shock are not relevant to PNs. As we will see later, such differences are due to the fact that the mean free path of neutrals and PUIs in PNs is much shorter than in the solar wind, and the source of PUIs in PNs is different than that in the solar wind-ISM interaction. Hence, in this section we describe the properties of solar wind and termination shock PUIs that are appropriate to consider in the context of PN wind shocks. For a complete description of solar wind and termination shock processes — including references to additional papers concerning the solar wind, its termination shock, and its interaction with the ISM — the reader is directed to Zank et al. (2010).

The schematic solar wind flow structure is drawn in Fig. 1. As shown schematically in the diagram (and will be quantitatively derived later in the paper), neutral atoms in the ISM have a very long mean free path to collision, and can penetrate to several AUs from the sun (see review in Zank 1999). There they are ionized and instantaneously picked-up by the

magnetic field in the solar wind; these particles therefore become PUIs. After being picked up, the PUIs experience scattering and isotropization by either ambient or self-generated low-frequency electromagnetic fluctuations in the solar wind plasma (Zank 1999). As they are now isotropized, the bulk velocity of the PUIs is that of the solar wind. Namely, the average location of the PUIs, as they gyrate about the interplanetary magnetic field, comoves with the solar wind; but their temporary speed at each moment relative to that location is about equal to the solar wind speed (e.g., Figs. 3.8 and 3.13. in Zank 1999), as they have high kinetic energy (~ 1 keV). In essence, the solar wind protons form a relatively cold “core” about which is superimposed a dilute halo of energetic PUIs. The PUIs suffer adiabatic cooling and energy diffusion, and their distribution with energy changes with distance from the Sun (e.g., Fig. 3.9 in Zank 1999). They also can heat the cold core proton distribution of the solar wind (Zank 1999). As we will see later, in PNs we require the PUIs to form close to the termination shock, and these processes are not significant. When they cross the reverse shock they gain relatively more energy than the thermal particles.

The existence of PUIs in the solar wind was suggested a long time ago to explain the overabundance of O and N in cosmic rays between 5-30 MeV (Fisk et al. 1974; Hovestadt et al. 1973; also see review in Zank 1999). This idea (Zank et al. 1996) was recently revisited (Richardson 2008) in the context of Voyager 2’s measurement for the temperature of the solar wind termination shock, which was much lower than the hydrodynamic value expected from equation 1 (Richardson et al. 2008). Specifically, at the time when Voyager 2 crossed the termination shock, August 30 to September 1 2007, the post-shock temperature was $\sim 10^5$ K — not $\sim 10^6$ K, as predicted by equation 1 — and the post-shock flow remained supersonic (Richardson et al. 2008). The explanation for this deviation from the simple hydrodynamic post-shock conditions is that most of the energy in the post shock region (region SW2 in Fig. 1) is carried out by suprathermal particles, i.e., PUIs. The pickup ions make up $\sim 20\%$ of the sheath plasma and have energies of ~ 6 keV in the heliosheath region SW2 (Richardson 2008), as compared with ~ 1 keV per nucleon in the pre-shock region (SW1 in Fig. 1). Indeed, the presence of these energetic particles was deduced from low-energy ions measured by Voyager 2 (Decker et al. 2008), and have been theoretically shown to explain the measured post-shock solar wind temperature (e.g., Fahr & Chalov 2008; Wu et al. 2009; Zank et al. 2010).

The chain of the physical processes in the solar wind and its termination shock is as follows (Fisk et al. 1974; Zank 1999; Zank et al. 1996, 2010). Because of their long mean free path, neutral atoms in the interstellar medium (ISM; region ISM1 in Fig. 1) are not influenced by the collisionless forward shock that is formed as a result of the relative motion of the sun and the ISM. Moreover, many of the neutral atoms are neither influenced by the shocked solar wind (region SW2) nor by the outer region of the pre-shock solar wind (SW1;

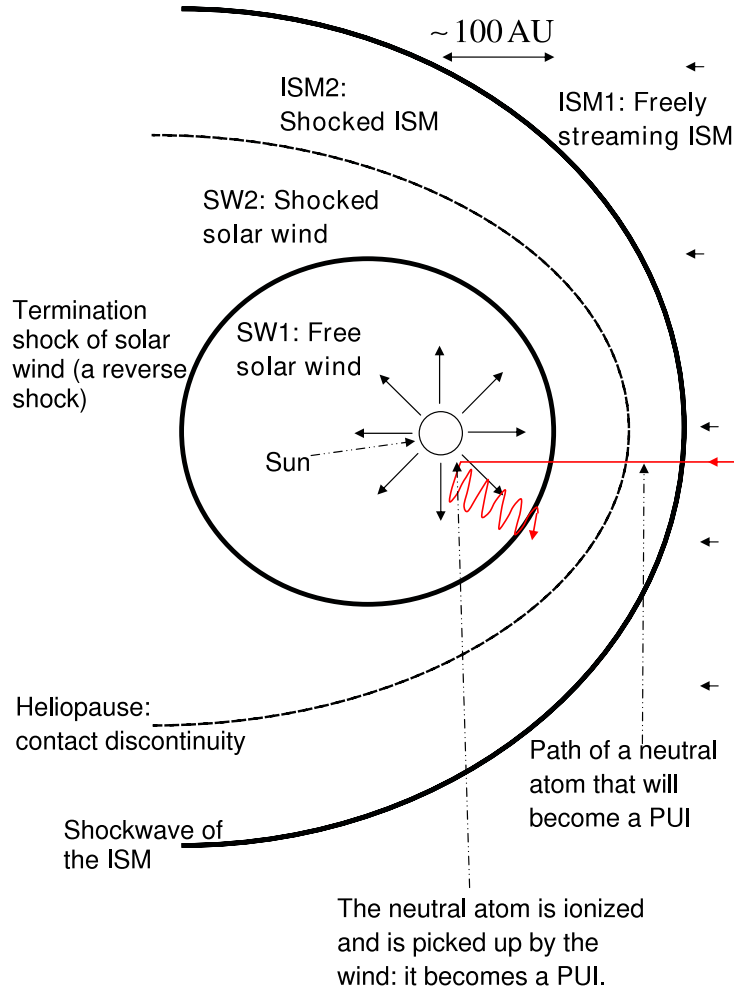


Fig. 1.— Schematic (not to scale) drawing of the interaction of the solar wind with the ISM. The ISM flows from right to left. The trajectory of the neutral ISM atom that turns into a PUI (see text) is schematically depicted by a line (in red).

for a detailed description see Zank 1999 and Zank et al. 2010). Only when they reach the inner regions close to the sun, $\sim 1 - 10$ AU, are they efficiently ionized by either charge exchange with the solar wind ions or by the solar UV flux (e.g., Vasyliunas & Siscoe 1976). Subsequently, the now-charged particles are picked up by the magnetized solar wind. Their kinetic energy per unit mass relative to the solar wind is given by

$$e_{\text{PUI}} \sim (1/2)v_{\text{sw}}^2 \simeq 1 \text{ keV nuc}^{-1}, \quad (2)$$

where $v_{\text{sw}} \sim 500 \text{ km s}^{-1}$ is the solar wind velocity. With this high average particle energy the PUI pressure dominates in the outer heliosphere (region SW1) (e.g., Zank et al. 2010 and references therein). As they cross the termination shock from SW1 to SW2, the PUIs can acquire energies of up to $\sim 100 \text{ MeV nuc}^{-1}$ (Ellison et al. 1999); but only a very small number of PUIs reach such high energies. The average gain of energy by the PUIs is (Fahr & Chalov 2008; eq. 8 in Zank et al. 2010)

$$\Delta E_{\text{PUI}} \simeq E_{\text{PUI}} (s^2 - 1), \quad (3)$$

where E_{PUI} is the pre-shock energy of the PUIs, while $s = \rho_2/\rho_1$ is the compression ratio, and throughout this paper it is assumed that the adiabatic index is $\gamma = 5/3$. Because of the PUIs, the compression factor of even a strong shock is < 4 (Zank 1999). The process of formation of PUIs results in a reduction in the bulk kinetic energy of the wind and the heating of the gas, both of which reduce the upstream Mach number (Zank 1999). The shock compression ratio found by Voyager 2 is ~ 2.4 (Richardson et al. 2008). We note that Stone et al. (1996) deduced a compression ratio of 2.63 ± 0.14 in the solar termination shock in 1994. They based their estimate on the energy spectra of anomalous cosmic rays measured by the Voyager and Pioneer spacecraft during 1992-1994.

Overall, for the PUIs to carry 90% of the postshock energy, the energy of the PUIs before the shock should be $E_{\text{PUI}} \simeq 0.2E_{t1}$, where E_{t1} is the total energy of the preshock wind, which is practically the kinetic energy of the pre-shock wind. The energy of the pre-shock PUIs per unit mass is given by equation (2); that of the wind's kinetic energy is about the same. Therefore, by equation (3), the number of the PUIs should be ~ 0.2 times that of the wind particles. Indeed, using the PUIs flux at the nose of the heliosphere calculated by Cummings & Stone (1996), Ellison et al. (1999) find the density of the PUIs at the termination shock to be ~ 0.2 times that of the thermal solar wind. Similar values were found by Richardson (2008) and Wu et al. 2009.

3. THE SOLAR WIND SHOCK VS. THE FAST WIND SHOCK IN PLANETARY NEBULAE

With the physics of the solar wind termination shock in mind, we turn to examine the termination shock of the fast wind blown by the central star of PNs (CSPN). In Figure 2 we present the schematic flow structure, while in Table 1 we compare several properties of PNs with those of the solar wind interaction with the ISM. We expect that more can be learned about PNs by comparison to the solar wind interaction with the ISM, but in this work, we limit ourselves to the role of PUIs.

As we show here and in Sec. 4, if PUIs exist and represent an important temperature-regulating process in PNs, then perhaps the most significant difference between the solar wind and PNs is the source of the PUIs. The source of the PUIs in the solar wind are neutral atoms that penetrate from the ISM. The mean free path for the neutral atom to collide with the shocked solar wind is large, and they can easily reach the pre-shock solar wind. The situation in the case of PNs is the opposite. We take a compression ratio of 2.4 as found in the solar termination wind (Richardson et al. 2008), and find the postshock ion density in a spherical wind to be

$$n_{2i}(\text{post}) = 1 \left(\frac{\dot{M}_w}{10^{-7} M_\odot \text{ yr}^{-1}} \right) \left(\frac{r_s}{5000 \text{ AU}} \right)^{-2} \left(\frac{v_w}{1000 \text{ km s}^{-1}} \right)^{-1} \text{ cm}^{-3}, \quad (4)$$

where r_s is the shock radial distance, v_w is the velocity of the central wind (v_{sw} for the sun and v_f for PNs), and \dot{M}_w is the mass loss rate of the wind.

In Table 1 we compare the wind parameters of the solar wind with those of PNs. It is apparent that the largest difference between the two lies in the fast wind mass loss rate. While the shock in PNs can be at $\sim 1000 - 10^4$ AU, which is only 10-100 times the shock radius of the solar wind, the mass loss rate is $\sim 10^{-8} - 10^{-6} M_\odot \text{ yr}^{-1}$, which is more than five orders of magnitude larger than that of the solar wind. The wind velocities are similar. For a collision cross section of $\sigma \simeq 3 \times 10^{-16} \text{ cm}^2$ (Heng & Sunyaev 2008 and references therein) the mean free path of neutral atoms in the post-shock solar wind region is $\lambda_N \simeq 10^5 \text{ AU} \gg r_s$. For an “optimistic” case in which these neutral atoms might penetrate deeply into the PN $r_s \simeq 2 \times 10^4 \text{ AU}$, $\dot{M}_w = 4 \times 10^{-8} M_\odot \text{ yr}$ and $v_w \simeq 2000 \text{ km s}^{-1}$ (values similar to those determined for NGC 6543; Kastner et al. 2008), we find $\lambda_N \simeq 2 \times 10^4 \text{ AU} \simeq r_s$. Even in this case, the mean free path is not much larger than the shock radius. However, such a large bubble is formed at a late stage, when the central star has already ionized the entire PN dense shell (regions AGB1 and AGB2 in Fig. 2), and there is no source of a large number of neutral atoms that can penetrate through the shocked fast wind without becoming ionized. Hence, for many (if not most) PNs the shock radius is smaller and the mass loss rate is

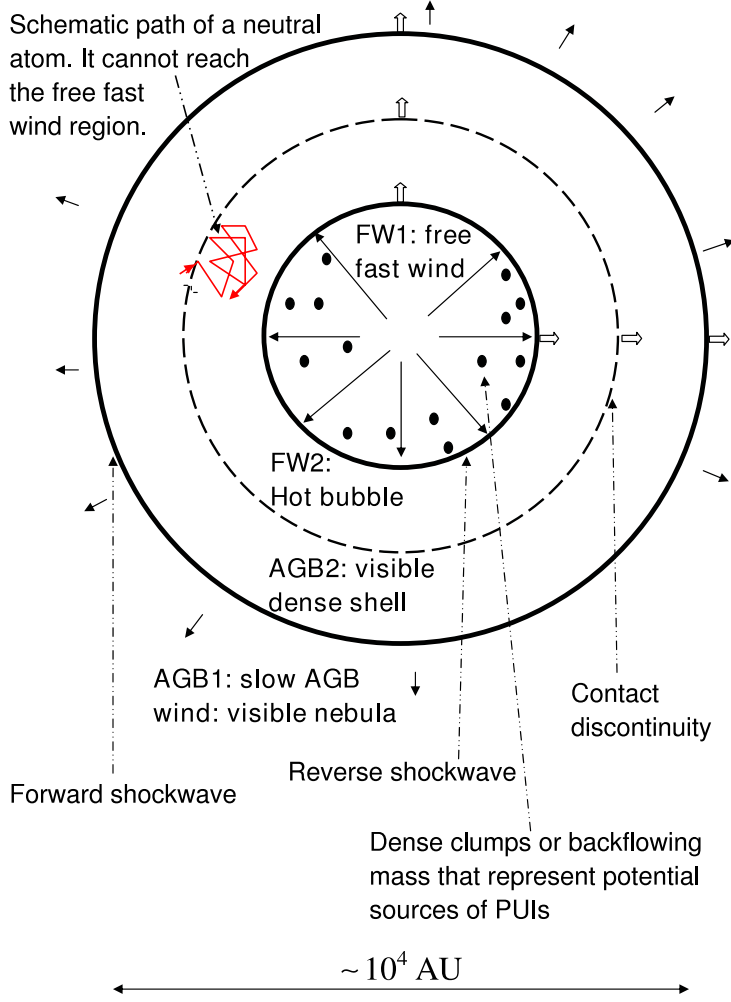


Fig. 2.— Schematic (not to scale) drawing of the interaction of the wind blown by the central star of the planetary nebula (CSPN) with the slow wind blown by the progenitor AGB star. Arrows show the flow, while double arrow indicate that the entire structure expands in the radial direction. Because of the much higher density than in the case of the solar wind, neutral atoms cannot penetrate the shocked fast wind region (FW2) and reach the pre-shock fast wind region; this is depicted by the zig-zag (red) line. PUIs that are formed close to the CSPN will lose their energy before reaching the reverse shock. Therefore, any significant source of PUIs must originate in slowly moving clumps inner to, and close to, the reverse shock.

Table 1: Comparison of the Solar Wind and PN Fast Winds

Property	Solar wind	Winds in PNs
Wind velocity (km s^{-1})	$v_{\text{sw}} \simeq 500$	$v_f \sim 500 - 1500$
Mass loss rate ($M_{\odot} \text{ yr}^{-1}$)	$\dot{M}_{\text{sw}} \sim 3 \times 10^{-14}$	$\dot{M}_f \sim 10^{-6} - 10^{-8}$
Shock position r_s (AU)	$r_{\text{sw}} \sim 100$	$r_{\text{sf}} \sim 1000 - 10^4$
Wind density at r_s (g cm^{-3})	$\rho_{\text{sw}} \sim 10^{-27}$	$\rho_{\text{fw}} \sim 10^{-26} - 10^{-22}$
External region (g cm^{-3})	$\rho_{\text{ISM}} \sim 10^{-24}$	$\rho_{\text{AGB}} \sim 10^{-20} - 10^{-17}$
Mean free path ⁽¹⁾ λ_N (AU)	$\lambda_{\text{SW2}} \sim 10^5$	$\lambda_{\text{FW2}} \sim 1 - 10^4$
λ/r_s	$\sim 10^3$	$10^{-3} - 1$
PUI stopping time ⁽²⁾ (years) t_s	$\sim 10 - 100$	$\sim 1 - 10$
Hot region age ⁽³⁾ (years) t_{age}	~ 1	$\sim 10^3$
Preshock flow time (years) t_f	~ 1	$\sim 10 - 100$
t_s/t_f	$\sim 10 - 100$	$\sim 0.01 - 1$
Ionization structure of the outer region	The ISM is mostly neutral.	During the PN phase the entire outer region is ionized.
Source of PUIs	ISM outside the shocked regions.	Backflowing mass or slow clumps embedded in the fast wind.

NOTES: (1) The mean free path is for neutral particles moving through the shocked region of the solar wind and fast wind, respectively. (2) The stopping time of the PUIs in the pre-shock (free wind) region. In the hot bubble the stopping time is longer. (3) In the solar wind the temperature is measured near the termination shock, and the age of the shocked wind is very short. In PNs the hot shocked gas remains in the hot bubble for > 1000 yr.

much higher, and therefore the mean free path is much smaller than the shock radius. We conclude that, unlike in the case of the solar wind, the PUIs are unlikely to originate in the regions outside the shocked fast wind.

4. PICK UP IONS (PUIs) IN PLANETARY NEBULAE

4.1. The Source of the Pick-Up Ions (PUIs)

By analogy with the solar wind, the fraction of PUIs in the fast wind of PNs should be $0.05 - 0.3$ if PUIs represent an important cooling mechanism for the post-shock gas. Here, we consider in detail two potential sources for the PUIs. We first note that the ablation rate of ions from Uranus-like planets that might orbited the progenitors of some PNs is of the order of $\sim 10^{-14} M_{\odot} \text{ yr}^{-1}$ (Soker 1999). The rate will be lower for minor planets. Even if we consider millions of minor planets associated with a PN progenitor star, this rate is too low to provide the PUI fraction necessary to explain the low temperature problem. In addition, these objects would reside relatively close to the center of the PN, such that the PUIs will reach (almost) equilibrium with the thermal gas before they reach the shock wave, as we show in section 4.2 below. As we see below, clumps (knots) in PNs are much larger than planets, and might contain enough mass; they are also more widely distributed within the PN, and their ablation (evaporation) rate is much higher. The formation of PUIs from clumps within PNs resembles in some aspects the formation of PUIs from comets (and even planets) in the solar system (regarding the potential cometary origin of solar wind PUIs see, e.g., Bzowski & Królikowska 2005).

Formation of neutral atoms in the hot bubble (post-shock gas) also likely does not represent a potential significant source of PUIs. The neutral atoms are not influenced by the magnetic field, and their mean free path is $\lambda_N \sim 200(n_e/1 \text{ cm}^{-3}) \text{ AU}$. This is the region from where neutral atoms formed by recombination in the hot bubble might reenter the preshock fast wind (FW1) region. However, in a typical (evolved) PN, there are not enough of these neutral atoms. The recombination time at the relevant temperature of $\sim 10^6 \text{ K}$ is $\sim 5 \times 10^6 (n_e/1 \text{ cm}^{-3})^{-1} \text{ yr}$, which is too long to supply the required neutral atom fraction of at least 0.05 of the total fast wind particles. If we consider the photoionization during the PN phase or the expectation that only a fraction of the recombined atoms will diffuse toward the upstream direction, then it is much less likely that recombining neutrals can be an important source of PUIs in PNs. At very early PN stages the shock radius r_s is very small and the recombination time of the postshock fast wind is short, and there is no significant ionizing radiation yet. However, if recombination proceeds fast enough to supply the neutral atoms, then the postshock gas cools rapidly via this same recombination process,

such that there would be no low temperature problem in very young PNs.

4.1.1. *Slowly moving clumps.*

We discuss here a case where the source of the PUIs in PNs is slowly moving clumps embedded in the fast wind. Whether such clumps start neutral or ionized, once ions (mainly protons) are released by the clumps, they would be picked up by the wind. Because of the large velocity difference between the slowly moving clumps and the fast wind, these ions behave like the PUIs in the solar wind. It is trivial to estimate the total mass that would need to be evaporated from the clumps to contribute sufficient PUIs to cool the postshock region: the bulk of the mass in the fast wind is lost over the first ~ 1000 years, with a mass loss rate of $\sim 10^{-8} - 10^{-6} M_{\odot} \text{ yr}^{-1}$ (Kastner et al. 2008) and, hence, for a PUI fraction of 0.1, the evaporated mass from the slowly moving clumps should be $\sim 10^{-6} - 10^{-4} M_{\odot}$. For > 1000 clumps, the mass in each clump could be very small, $\lesssim 10^{-7} M_{\odot}$. However, the clumps would need to be distributed in the inner volume of the PN.

The best studied case of slowly moving ($\sim 10 \text{ km s}^{-1}$) clumps are the cometary globules (or knots) in the Helix nebula (NGC 7293). Although the origin of these clumps (or knots) remains uncertain, their presence is well established (O’Dell et al. 2007 and references therein). The characteristic mass of individual knots is estimated to be $\sim 1 - 5 \times 10^{-5} M_{\odot}$ (O’Dell & Burkert 1997; Meaburn et al. 1992; Huggins et al. 2002; Meixner et al. 2005). Their total number in the inner region, which is engulfed in fast wind gas, is $\sim 10^4$ (O’Dell & Handron 1996; Hora et al. 2006). The total mass in the knots of the Helix nebula is therefore about three orders of magnitude above the required mass. The knot evaporation time scale during the early PN phase is $\sim 10^5 \text{ yr}$ (Matsuura et al. 2009). Therefore, the evaporation rate of slowly moving gas in the Helix is $\sim 10^{-6} M_{\odot} \text{ yr}^{-1}$, about an order of magnitude higher than required. For smaller clumps the evaporation rate would be higher, and a mass of only $\sim 10^{-4} M_{\odot}$ might be sufficient to reduce the post-shock temperature of the fast wind.

Although there are other PNs with cometary globules similar to those observed in the Helix nebula (see, e.g., images of the Ring Nebula at the Hubble Heritage website¹ and of the narrow-waist bipolar PN NGC 6302 in Szyszka et al. 2009), we caution that the Helix is not an ideal case to consider for purposes of evaluating whether slow-moving clumps could serve as a source of PUIs. The Helix has no detectable diffuse (hot bubble) X-ray emission (Guerrero et al. 2001) and, even at early PN stages, its (apparent nearly pole-on bipolar)

¹<http://heritage.stsci.edu/1999/01/index.html>

nebular geometry may not have been conducive to the presence of such emission (Kastner et al. 2008). It therefore remains to be determined whether the presence of Helix-like clumps, either neutral (as in the Helix) or ionized, are a common feature of PNs.

4.1.2. *Back-flowing material.*

Backflowing material might supply plenty of PUIs, in addition to the slowly moving clumps. Accretion of backflowing material during the post-AGB phase was considered in several papers (Mathis & Lamers 1992; Bujarrabal et al. 1998; Zijlstra et al. 2001; Soker 2001) to explain other properties of PNs such as longer post-AGB evolution time. This type of accretion is driven by the gravity of the central star that acts efficiently on dense clumps (Soker 2001). The dense clumps are formed during the AGB phase, probably requiring the presence of a binary companion (Soker 2010). Post AGB accretion rates of $\gtrsim 10^{-7} M_{\odot} \text{ yr}^{-1}$ were considered by Soker (2001); this theoretical study showed that conditions might exist for a total accreted mass of $\sim 0.1 - 0.001 M_{\odot}$. Before the PN phase the clump is neutral. After the beginning of the PN phase, which is the phase relevant to us, the outer regions of the clumps are ionized and evaporated. These ions could be picked up by the fast wind. If a fraction of $\sim 10^{-3} - 0.1$ of the accreted mass were picked up by the fast wind, this would be sufficient to substantially reduce the post-shock temperature.

Backflow might persist to the PN phase (Frankowski & Soker 2009). The backflow in this case is driven by the rapid increase in the pressure of the dense, slowly expanding main shell of the PN. The rapid increase in pressure occurs when the central star starts to ionize the nebula and the nebular temperature increases from $\lesssim 10^3 \text{ K}$ to 10^4 K in a short time. A rapid increase in the pressure of the shell may also result in instabilities that form ionized clumps (Frankowski & Soker 2009). In the PN phase the backflow rate is only $\sim 10^{-9} - 10^{-6} M_{\odot} \text{ yr}^{-1}$ over thousands of years, and the total backflowing mass is $\sim 10^{-5} - 10^{-3} M_{\odot}$. This is sufficient for the PUI process to be important, because over thousands of years the mass loss rate of the fast wind substantially declines, and so does the required PUI mass.

The backflowing gas fulfills the condition that the source of the PUIs be near the reverse shock, and just interior to it, such that the PUIs have no time to reach equilibrium with the thermal pre-shock fast wind (see section 4.2). According to Frankowski & Soker (2009) the backflowing gas is well protected as it falls within the shocked fast wind zone. However, as clumps of gas cross the shock front (as they fall toward the center), they would become subject to the ram pressure of the fast wind. There they would be quickly decelerated, and could be destroyed, so as to provide a source of PUIs.

4.2. The stopping time of the PUIs

Even if the PUIs originate in the inner region, there is an additional requirement for PUIs to play a role in the low temperature problem. The PUIs that are formed in the pre-shock fast wind in PNs should not reach thermal equilibrium with the gas, neither before nor after passing through the shock. More quantitatively, the stopping time t_s of the PUIs needs to be longer than the relevant flow time. In the postshock region (the hot bubble) the relevant time is the PN age, $t_{\text{age}} \sim 10^3$ yr. For PUIs in the pre-shock wind the relevant flow time is the flow time from their origin to the shock. If they are forming a distance Δr inward to the shock, this time is

$$t_f \simeq 5 \left(\frac{\Delta r_s}{0.2 r_s} \right) \left(\frac{r}{5000 \text{ AU}} \right) \left(\frac{v_w}{1000 \text{ km s}^{-1}} \right)^{-1} \text{ yr.} \quad (5)$$

This requires the PUIs to originate far from the central star, where the density drops ($n \propto r^{-2}$) and in low mass loss rate PNs (as $n \propto \dot{M}$; see eq. 4); density and mass loss rate thus play a role in determining the stopping time (see below).

We can use Spitzer (1956) to estimate the stopping time (and hence the mean free path λ_{mfp}) of a high-speed PUI originating in the fast wind before it is stopped inside the shocked hot bubble ($T \approx 10^6$ K, $n_e \approx 1 \text{ cm}^{-3}$) and in the more extended cold nebula ($T \approx 10^4$ K, $n_e \approx 10^4 \text{ cm}^{-3}$). In the pre-shock wind we take the wind temperature to be $\sim 10^4$ K, where the ionizing radiation of the CSPN will balance adiabatic and radiative losses. Using Eq. (5-28) of Spitzer (1956), we write the typical time it would take a PUI to be stopped by dynamical friction in the pre-shock wind

$$t_s = \frac{k T M_+ V_+}{4 \pi e^4 n Z^2 Z_+^2 \ln \Lambda G(V_+/v_{\text{th}})} \\ \simeq 1.8 \left(\frac{T}{10^4 \text{ K}} \right) \left(\frac{M_+}{m_p} \right) \left(\frac{V_+}{1000 \text{ km s}^{-1}} \right) \left(\frac{n}{1 \text{ cm}^{-3}} \right)^{-1} \left(\frac{\ln \Lambda}{30} \right)^{-1} \left(\frac{G}{0.2} \right)^{-1} Z^{-2} Z_+^{-2} \text{ yr,} \quad (6)$$

where M_+ , Z_+ , and V_+ are the PUI mass, charge, and velocity, respectively; T , n , Z , and v_{th} are the temperature, density, charge, and thermal velocity of the ambient gas. Note that V_+ , the thermal velocity of the PUIs relative to the bulk of the wind, is equal to the bulk velocity of the wind that picks up the PUIs. The Coulomb logarithm $\ln \Lambda \simeq 20 - 30$, while G is a function of the velocity ratio and is tabulated by Spitzer (1956). The second line of Eq. (6) incorporates values appropriate for the fast PN wind.

In the pre-shock region the electron velocity is similar to the PUI speed relative to the wind, and the electrons stop the PUIs, while in the hot bubble the PUIs are slowed down most efficiently by ions. The reason is as follows. When the PUI velocity much exceeds the

thermal velocities, $t_s \propto T^{3/2}$ and is independent of V_+ . Indeed, the function G attains its maximum value and, hence, t_s is a minimum, for $V_+ = \sqrt{2kT/m}$. For a 10^3 km s^{-1} PUI this is approximately the case for the thermal ions in the hot bubble and for the thermal electrons in the cold nebula. Using equation (4) to find the density in the solar wind, and then plugging this value into equation (6), we find that the PUIs in the solar wind lose their energy on time scales much longer than the flow time scale (see Table 1).

Comparing equations (6) and (5), with the aid of equation (4), we find that for the PUIs not to lose their suprathermal status before the shock, the mass loss rate of the fast wind is required to be $\dot{M}_w \lesssim 10^{-7} M_\odot \text{ yr}^{-1}$ and the shock to be at $r_s \gtrsim 5000 \text{ AU}$. Both of these conditions apply to relatively evolved PNs, and hence are not a strong constraint, because the low temperature problem arises for PNs for which the fast wind speed is $v \gtrsim 10^3 \text{ km s}^{-1}$. Another constraint is that the PUIs source be close to the shock (§4.1.2), both for the flow time t_f to be short, and for the densities at the sites of PUI origin not to be too high.

In the postshock region the temperature is typically observed to be $\sim 3 \times 10^6 \text{ K}$ (Kastner 2007; Kastner et al. 2008), and the PUIs have been accelerated to $v \gtrsim 2000 \text{ km s}^{-1}$. This velocity comes from the energy gain in the shock by a factor of $\sim s^2$ (Fahr & Chalov 2008; Zank et al. 2010; see equation 3 here), where $s \simeq 2.5$ is the compression ratio at the shock, and we take the preshock thermal velocity to be $\gtrsim 800 \text{ km s}^{-1}$. For these parameters $G \simeq 0.1$ (Spitzer 1956). These values bring the loss time scale to $t_s \simeq 2000 \text{ yr}$, given the default values of the other parameters in equation (6). This is longer than the age of a PN at that stage.

Adopting $t_s \sim 1000 \text{ yr}$, a PUI with $V_+ \simeq 2000 \text{ km s}^{-1}$ travels a distance of $\sim 4 \times 10^5 \text{ AU}$. Downstream (away from the shock), the gas in the bubble likely would be further compressed, so this distance will be proportionally shorter. Hence, within $\sim 100 \text{ yr}$ the PUIs can travel a distance of $\sim 10^5 \text{ AU}$. If they are not deflected, they could reach the dense nebular shell of a small PN (the visible shell where $T \sim 10^4 \text{ K}$), where they will quickly decelerate ($t_s \simeq 1 \text{ yr}$) and deposit their energy. However, the deflections and tangled magnetic field would likely prevent them from directly reaching the visible dense shell on a straight trajectory.

As noted, in old PNs, where $r_s \gtrsim 5000 \text{ AU}$, and $\dot{M}_w \lesssim 10^{-7} M_\odot \text{ yr}^{-1}$, the PUI stopping time is larger than the PN age, $t_s \gtrsim 1000 \text{ yr}$, and the PUIs might efficiently carry energy out of the hot bubble (if their number is large enough). However, in younger PNs this is less likely. For example, in BD+30°3639 the velocity is $\sim 700 \text{ km s}^{-1}$ and the mass loss rate is estimated to be $\dot{M}_w \sim 10^{-6} M_\odot \text{ yr}^{-1}$ (Leuenhagen et al. 1996; Marcolino et al. 2007). The outer hot bubble radius is $\sim 5000 \text{ AU}$ and the shock radius r_s is smaller (Kastner 2008), so the PUIs in the preshock region will lose their energy very quickly if they are not formed very near the shock wave. On the other hand, in this young PN, it is also possible that a

large mass of dense clumps would be formed by instabilities close to the shock wave, and that such clumps could supply the required number density of PUIs to cool the newly-formed hot bubble.

The main conclusion of this section is that if the PUIs originate close to the center, at $r_o \lesssim 10^3$ AU, they will lose their energy before entering the shock wave. If PUIs are to play a role in cooling the hot bubble, they must originate just inside the shock, such that $r_o \lesssim r_s$, with $r_o \gtrsim 3 \times 10^3$ AU (where the exact value depends on the actual mass loss rate of the fast wind). Hence, PUIs might play a role in PNs that are not smaller than a few 10^3 AU as long as the fast-wind mass loss rate is also low, of the order of $\dot{M}_w \lesssim 10^{-7} M_\odot \text{ yr}^{-1}$. In such PNs, backflowing gas and slow clumps can supply the required PUIs.

5. SUMMARY

Slowly moving ions that are picked up by the solar wind, called pick up ions (PUIs), carry most of the energy in the post shock region (Fig. 1); their presence explains the unexpectedly low temperature of the shocked solar wind gas (e.g., Richardson et al. 2008; Decker et al. 2008; Fahr & Chalov 2008; Wu et al. 2009). Motivated by these results for the solar wind, we examined whether a similar process can occur in planetary nebulae (PNs). In PNs the flow structure is similar, although not identical, to that of the solar wind (Fig. 2). Hence, PUIs may also be present in PNs. If so, the presence of PUIs might explain the general finding that the temperature of the hot bubble formed by the post-shock gas in most PNs (region FW2 in Fig. 2) is lower than that expected from straightforward hydrodynamic shock calculations — a discrepancy (dubbed the *low temperature problem*) for which several alternative explanations have been proposed but no clear consensus has emerged (see section 1).

We demonstrate that the presence of PUIs might explain the PN low temperature problem. However, whereas in the case of the solar wind the neutral atoms that turn into PUIs penetrate the pre-shock solar wind region from the interstellar medium (ISM; see the schematic particle trajectory drawn in Fig. 1), in PNs the densities are much higher in all regions, and neutral atoms cannot penetrate from regions outside the hot bubble so as to reach the pre-shock region (region FW1 in Fig. 2). Instead, we hypothesize that, in PNs, the PUI source would most likely be slowly moving clumps embedded in the fast wind or jets. These clumps are formed by instabilities or from backflowing cold gas, as discussed in section 4.1. For the PUIs behind the shock not to thermalize too rapidly, the PUI stopping time (given by equation 6) cannot be shorter than the typical flow time. This condition is met by a large margin for the solar wind, but only marginally in PNs, and only under certain

circumstances. In particular, we find that the conditions under which PUIs might play a role in moderating the hot bubble temperatures in PNs are (a) the slowly moving clumps (the source of the PUIs) must be located just inside the shock ($r_o \lesssim r_s$, with $r_o \gtrsim 3 \times 10^3$ AU), and (b) the mass loss rate cannot be too large, i.e., $\dot{M}_w \lesssim 10^{-7} M_\odot \text{ yr}^{-1}$.

It is worth considering whether the fast wind itself would decelerate as a result of the incorporation of PUIs. To play any significant role in the fast wind shock, the PUI number fraction should be $\xi_P \gtrsim 0.1$ of the total fast wind particle number density. As the typical thermal velocity of the preshock PUIs (V_+) is that of the bulk velocity of the wind, the bulk energy of the wind is reduced to $1 - \xi_P$ times its original value. This is a small change that cannot account by itself for the low temperature problem. Even if we take this fraction to be $\xi_P = 0.3$, the reduction in energy is $\sim 30\%$, and the bulk wind speed is reduced by only $\sim 15\%$. As other uncertainties in the winds interaction in PNs are larger, there is unlikely to be any significant reduction in the preshock velocity of the fast wind as a result of the PUI formation process.

Our results can apply for the case where the hot bubble are formed by jets. In these cases two opposite lobes are formed by two jets. Namely, this process can occur in symbiotic nebulae. Finally, it is evident from our study that the comparison of the solar wind termination shock with that of the fast winds in PNs has its own scientific interest beyond the low temperature problem. Future studies of this potential correspondence should shed further light on the evolution of the shocked fast wind in PNs.

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